

X-621-68-233

PREPRINT

NASA TM X- 63305

THE LATITUDINAL TEMPERATURE STRUCTURE OF THE TOPSIDE IONOSPHERE

GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

Hard copy (HC) 3.00

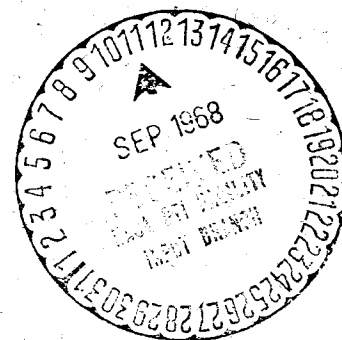
Microfiche (MF) 165

ff 653 July 65

H. G. MAYR
L. H. BRACE
W. CREVIER

N 68-33206
(ACCESSION NUMBER) (THRU)
92
(PAGES)
TMX-63305
(NASA CR OR TMX OR AD NUMBER) (CODE)
(CATEGORY) 13

JUNE 1968



GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

**THE LATITUDINAL TEMPERATURE STRUCTURE OF THE
TOPSIDE IONOSPHERE**

H. G. Mayr, L. H. Brace and W. Crevier

Aeronomy Branch

June 1968

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

THE LATITUDINAL TEMPERATURE STRUCTURE OF THE TOPSIDE IONOSPHERE

by

H. G. Mayr,* L. H. Brace and W. Crevier**

Aeronomy Branch

ABSTRACT

By solving the energy and the continuity equations for O^+ and H^+ , the observed latitudinal electron temperature distribution observed by Explorer XXII can be reproduced up to latitudes of 60° with a trough at the equator and maxima at middle latitudes. At geomagnetic latitudes above 60° , however, the theoretical temperatures decrease significantly below the observed temperatures. It is suggested that the depletion of H^+ observed at high latitude by ion mass spectrometers could be related. Such a depletion of the light ion population causes the electron cooling rate to the neutral atmosphere, to decrease; an effect that would enhance the temperature.

*NAS-NRC Research Associate, now with NASA.

**Supported by NASA Grant NGR 21/002/096, presently at the Institute for Fluid Dynamics and Applied Mathematics, University of Maryland, College Park.

PRECEDING PAGE BLANK NOT FILMED.

CONTENTS

	<u>Page</u>
ABSTRACT	iii
INTRODUCTION	1
THEORY	2
RESULTS AND DISCUSSION	6
CONCLUSION	11
REFERENCES	13

THE LATITUDINAL TEMPERATURE STRUCTURE OF THE TOPSIDE IONOSPHERE

by

H. G. Mayr, L. H. Brace and W. Crevier

Aeronomy Branch

INTRODUCTION

The electrostatic probe experiment on Explorer XXII reveals that during daytime the electron temperature T_e at 1000 kilometers exhibits a minimum at the equator and maxima at middle latitudes. An opposite trend is apparent in the electron density N_e , which shows a maximum at the equator and minima at middle latitudes (Brace, Reddy, Mayr (1967), Brace, Mayr, Reddy (1968)). Although from simple energetic considerations such an inverse relationship between temperature and density is suggested, the relationship is not simple if one actually considers the very complex interrelation between the particle and energy balance of the ionosphere on a global basis. In the topside ionosphere temperature and density are related through numerous processes, all of which have to satisfy the energy and continuity equations. An additional complication is that these relations have to be satisfied in field tubes of greatly different spatial extension, as various latitudes are considered.

The subject of this paper is to report on the computation of the latitudinal temperature structure under the assumption of steady state and field aligned diffusion. A discussion of the heating and cooling rates above 1000 km will show that the collisional energy loss remains important at high altitudes thus

reemphasizes the importance of neutral hydrogen for the thermal balance of the topside ionosphere (Brace et al., 1967, Mayr et al., 1967). A comparison between the computed and observed temperatures will provide evidence for the dynamic state of the protonosphere which is consistent with ion composition measurements.

THEORY

The basic form of the energy and continuity equations as well as the method of their integration employed here are almost identical to the treatment in Mayr, Brace, Dunham (1967). Some of the features common to this and the previous study are briefly reviewed here.

The physical processes entering the ion continuity equations are: charge exchange between ions and neutrals, photoionization of O and H, and ambipolar diffusion along field lines. It is assumed that at altitudes below 400 km H^+ is in chemical equilibrium with O, H, and O^+ through the charge exchange reaction, thus providing the lower boundary condition for the integration of the H^+ continuity equation. The boundary condition for O^+ requires that the electron density be in agreement with measurements from Explorer XXII at 1000 km (Brace, Reddy, Mayr, 1967). These measurements were made during equinox conditions; so we postulate that the solutions of the continuity equations are symmetrical with respect to the equatorial plane. This implies that the ion fluxes and density gradients are zero at the equator, thus providing the necessary additional boundary conditions for the second order continuity equations.

Several modifications were made of the earlier treatment of the energy balance. They are discussed here in detail. The assumption of thermal

equilibrium ($T_e = T_i$) was dropped. Neglecting ion heat conduction the energy equations for electrons and ions become

$$\frac{3}{2} k N_e \frac{\partial T_e}{\partial t} = \kappa B \frac{\partial}{\partial s} \left(\frac{T_e^{5/2}}{B} \frac{\partial T_e}{\partial s} \right) + p N_e + q[O] - \frac{(T_e - T_i)}{T_e^{3/2}} N_e (K_{O^+} [O^+] + K_{H^+} [H^+]) = 0 \quad (1)$$

$$\frac{3}{2} k N_e \frac{\partial T_i}{\partial t} = \frac{(T_e - T_i)}{T_e^{3/2}} N_e (K_{O^+} [O^+] + K_{H^+} [H^+])$$

$$- \sum K_{X+Y} [X^+] [Y] (T_i - T_n) = 0 \quad (2)$$

with the same notations as in Mayr, Brace, Dunham (1967). The coefficients K_{O^+} , K_{H^+} in the loss rates for electron-ion collisions are according to Brace, Spencer, Dalgarno (1965).

The electron heat conduction term in Eq. 1 is density independent while the energy gain and loss terms increase with increasing plasma and neutral concentrations. Thus the importance of heat conduction relative to loss and gain will be smallest at low altitudes. Our estimations indicate that during daytime heat conduction contributes not more than 10% to the thermal energy balance at 300 km. Therefore, at this altitude we neglect heat conduction and calculate the

electron and ion temperatures using Eqs. 1 and 2. T_{300} together with the equatorial symmetry condition

$$\left(\frac{\partial T_e}{\partial s}\right)_{\text{equator}} = 0$$

serve as boundary conditions for the integration of Eq. 1 up to the equator.

The rate of non local heating, expressed in Eq. 1 as pN_e , was described in a more realistic form than in the previous paper. It was assumed that the escaping fast electrons, responsible for this energy input (Geisler and Bowhill (1965)), have an initial energy of 10 eV at 300 km with velocities directed parallel to the magnetic field. These electrons lose energy to the ambient plasma at a rate of

$$\frac{\partial E}{\partial s} = -K \frac{N_e}{E}; \quad K = 1.95 \times 10^{-12} [\text{eV}^2 \text{ cm}^2] \quad (3)$$

according to Butler and Buckingham (1962), Dalgarno et al. (1963). Electrons traveling up along the field line thus have an energy distribution

$$E_u = \left(E_0^2 - 2K \int_{s_0}^s N_e ds \right)^{1/2}; \quad E_0 = 10 \text{ eV} \quad (4)$$

where the subscript u stands for the upgoing electrons. At the equator the energy will be

$$E_e = \left(E_0^2 - 2K \int_{s_0}^{s_e} N_e ds \right)^{1/2} \quad (5)$$

which is the energy that is carried up by fast electrons from the other hemisphere assuming symmetry about the equator. These electrons have an energy distribution of

$$E_d = \left(E_e^2 - 2K \int_s^{s_e} N_e ds \right)^{1/2} \quad (6)$$

when going downwards.

The total flux of these electrons through the field tube remains constant and thus the flux density varies as

$$j = j_0 \frac{B_0}{B} \quad (7)$$

where B is the magnetic field intensity along a field line, B_0 is its value at 300 km, and j_0 is the flux density at this altitude. Considering Eq. 7 and Eq. 3 the energy input per unit volume and time is then

$$pN_e = -j \frac{\partial E}{\partial s} = K \frac{j_0}{B_0} \frac{B}{E} N_e \quad (8)$$

Combining the energy contributions from the upgoing and downgoing electron fluxes, p takes the form

$$p = \frac{Kj_0}{B_0} B N_e \left(\frac{1}{E_u} + \frac{1}{E_d} \right) \quad (9)$$

From Eq. 4 and Eq. 6 (where E_u and E_d are defined) it is evident that theoretically the energy expressions may become zero. However, Eq. 3 from which they were derived is only valid for electron energies above the thermal energy of the ambient electrons which is in the order of 0.5 eV. The energy loss rate of electrons approaching this value will, according to Eq. 3 be up to 20 times greater than the rate at the original energy of 10 eV. As the electrons become thermalized the loss rate must drop from this high value to zero. The simplest description of this term is to assume a discontinuous drop in the loss rate to zero for energies below some arbitrary chosen cut off energy. We have chosen this energy as 2 eV. As a result of using this cut off, about 20% of the fast electron energy was not considered and consequently the electron flux we arrived at will be high by about the same percentage.

RESULTS AND DISCUSSION

Using Jaccia's model for low solar activity ($T_n = 830^\circ\text{K}$ and $[O]_{500} = 7.5 \times 10^6/\text{cc}$) and using $[H]_{500} = 2 \times 10^5/\text{cc}$ the energy and continuity equations were solved. The electron temperature as a function of latitude is shown in solid lines for several altitudes in Figure 1. For comparison, the observed latitudinal temperature distribution at 1000 km (from Explorer XII, Brace, Reddy, Mayr (1967)) is also presented. Good agreement exists up to 60° geomagnetic latitude;

the trough at the equator and the maximum at middle latitude are reproduced.

This was achieved by employing the values

$$j_0 = 7.5 \times 10^8 / \text{cm}^2 \text{ sec}$$

$$q = 4 \times 10^{-18} \text{ erg/sec}$$

at each latitude.

To gain some insight into the physical processes that form the latitudinal temperature structure we present in Figure 2 the various energy rates integrated over field tubes above 1000 km (with 1 cm^2 basis area). The dashed line shows the energy input due to fast electrons, the dashed-dotted line shows the energy loss between plasma and neutral atmosphere and the solid line shows the difference between input and loss which is equal to the heat flux ($\alpha T_e^{5/2} \partial T_e / \partial s$) at 1000 km.

The latitudinal variation of the energy input above 1000 km depends strongly on the rate at which the fast electrons lose their energy at lower altitudes. Near the equator, the electron density is high and almost all of the energy is absorbed below 1000 km. Thus only a small amount of energy can heat the ionosphere above this height. With increasing latitude the electron density decreases and an increasingly larger proportion of the energy becomes available as input at higher altitudes. Above 40° the latitudinal variation in the electron density is small and therefore the energy input above 1000 km stays constant.

The total rate of energy loss due to collisions in field tubes above 1000 km (also shown in Figure 2) depends proportionally on the ion content and on the density of the neutral atmosphere (primarily neutral hydrogen). Additionally,

the loss rate is a function of the ion and neutral species involved in this loss process. Hydrogen ions lose their energy most effectively to hydrogen atoms, and similarly oxygen ions cool most rapidly to neutral oxygen but at a rate 4 times lower than the loss rate between H^+ and H (Brace, Spencer, Dalgarno (1965)). At the equator, the loss rate is small because of the small field tubes and their particle population. With increasing latitude the field tube volume increases and so does the total ion content as evident from Figure 3 (where the ion content above 1000 km is shown as a function of latitude). The result is an increase of the energy loss rate. Between 20° and 40° latitude the ion content increases further and there is a small increase in the population of neutral particles. But simultaneously the mean ion mass increases (shown in Figure 4) thus decreasing the effectiveness of the cooling process. The net result is that the loss rate remains nearly constant. At latitudes above 40° the field tube volumes strongly increase and therefore the contact between plasma and neutral atmosphere involves significantly larger particle populations. The net effect is that the loss rate rapidly increases at higher latitudes.

The variation of the heat flux (in solid line in Figure 2) reflects the very different behavior of input and loss rates with latitudes. Near the equator both energy and loss rates are low. The loss exceeds the gain and this requires a negative temperature gradient along field lines that contributes to the low equatorial temperature. Up to middle latitudes the energy input increases while the loss function shows little variability. Therefore the heat flux increases as does the temperature. Above 40° the energy loss starts to increase and the input levels off. The result is that the heat flux forms a maximum at 50° where T_e is also highest. Beyond this latitude the energy loss dominates and leads to

the rapid decrease of the heat flux and to a similar decrease of the temperature at high latitudes.

Figure 1 shows that at high latitudes (above 60°), the theoretical temperatures decrease significantly below the measured ones. This is also evident in the equatorial temperature profile of Figure 5. The temperature decreases at high altitudes (corresponding to high latitudes) in contrast to measurements by Serbu and Maier (1966) who report a steady increase of T_e with altitude, reaching temperatures of several thousand degrees at altitudes of a few earth radii.

The reason for this discrepancy may be that some of the assumptions in our model are not valid at high latitudes. It is possible that additional heat sources such as hydromagnetic waves or energetic particles are significant there. Another alternative is that the steady state and field aligned diffusion model, which does not allow for any proton fluxes is inappropriate at high latitudes. The former would mean an increase in the energy input, while the latter, as will be shown below, can result in a reduction of the energy loss mechanism; both effects would increase the temperature.

The ion composition which was simultaneously computed with the electron temperature was used to determine the mean ion mass, m^+ , at 1000 km. It is shown in Figure 4 in comparison with results deduced from OGO 2 (Taylor et al. (1968)). The agreement is good up to middle latitudes. However above 50° , where the discrepancy in the temperature also becomes apparent, the observed mean ion mass increases to its maximum value of 16 AMU, whereas the computed values of m^+ decrease to 3 AMU. This means that in our model the electron density scale height is too high by a factor of 5 and consequently the total ion content above 1000 km is too high. The effects on the thermal balance are

obvious. As shown earlier, the collisional energy loss rate is very sensitive to the plasma population and mean ion mass. A reduction of the proton content, in accordance with the mean ion mass observation, would thus lead to a reduction in the energy loss and this would increase the temperature.

An increase in the electron temperature would in turn raise the mean ion mass. However, it was demonstrated in Mayr, Brace, Dunham (1967) that the mean ion mass, observed at high latitudes, is far too high to be accounted for by the observed temperatures at 1000 km. Therefore one might postulate upward fluxes of protons that deplete the proton concentration. Two mechanisms could induce fluxes: the dynamic coupling between F_2 region and protonosphere as discussed by Hanson and Patterson (1964), or escape of protons in combination with diffusion across field lines, a mechanism that ties the high latitude depletion of H^+ to the plasmapause (Mayr, 1968).

A further consequence of the decrease of the ion concentration at high latitudes would be that the classical expression for the electron heat conductivity is no longer valid because of the long mean free path. For low densities it has to be modified with the result that the effective heat conductivity decreases and thus could account for the high temperatures observed by Serbu and Maier (1966) at high altitudes (Mayr and Volland (1968)).

CONCLUSION

It is concluded that in accordance with earlier papers (Brace, Reddy, Mayr (1967); Mayr, Brace, Dunham (1967)) collisional cooling between the plasma and the neutral atmosphere is still an important process above 1000 km. At the equator the loss rate is small but significant when compared with the low energy input. At high latitudes (above 50°) the loss process increases so strongly that it gains a dominating role in the thermal balance. Since neutral hydrogen is responsible for cooling the plasma above 1000 km its significance in the thermal structure of the topside ionosphere is apparent.

The failure to reproduce the measured high electron temperatures at high latitudes is found to be consistent with the discrepancy between the theoretical and observed mean ion mass. It suggests that proton fluxes deplete the protonosphere and thus account for a decrease of the energy loss in the protonosphere, an effect that would enhance the temperature.

REFERENCES

1. Brace, L. H., N. W. Spencer, and A. Dalgarno, Detailed behavior of the mid-latitude ionosphere from Explorer 17 satellite, Planetary Space Sci., 13, 647-666, 1965.
2. Brace, L. H., B. M. Reddy, and H. G. Mayr, Global behavior of the ionosphere at 1000 km altitude, J. Geophys. Res., 72, 265-283, 1967.
3. Brace, L. H., H. G. Mayr, and B. M. Reddy, The early effects of increasing solar activity upon the temperature and density of the 1000 km ionosphere, J. Geophys. Res., 73, 1607-1615, 1968.
4. Butler, S. T., and M. J. Buckingham, Energy loss of a fast ion in a plasma, Phys. Rev., 126, 1-4, 1962.
5. Dalgarno, A., B. M. McElroy, and R. J. Moffett, Electron temperatures in the ionosphere, Planetary Space Sci., 11, 463-484, 1963.
6. Geisler, J. E., and S. A. Bowhill, Exchange of energy between ionosphere and protonosphere, J. Atmospheric Terrest. Phys., 27, 1119-1146, 1965.
7. Hanson, W. B., and T. N. L. Patterson, The maintenance of the nighttime F-layer, Planet. Space Sci., 12, 979-997, 1964.
8. Mayr, H. G., L. H. Brace, and G. S. Dunham, Ion Composition and temperature in the topside ionosphere, J. Geophys. Res., 72, 4391-4404, 1967.
9. Mayr, H. G., The plasmopause and its relation to the ion composition in the topside ionosphere, NASA-Document X-621-67-570, to be published in Planetary Space Sci.

10. Mayr, H. G., and H. Volland, A model of the magnetospheric temperature distribution, NASA-Document X-621-67-569, to be published in J. Geophys. Res.
11. Serbu, G. P., and E. J. R. Maier, Low energy electrons measured on IMP2, J. Geophys. Res., 71, 3755-3766, 1966.
12. Taylor, H. A., Jr., H. G. Brinton, M. W. Pharo III, and N. K. Rahman, Latitudinal variation of the composition of the topside ionosphere; first results of the OGO-2 ion spectrometer. NASA Document X-621-68-202, to be published in J. Geophys. Res.

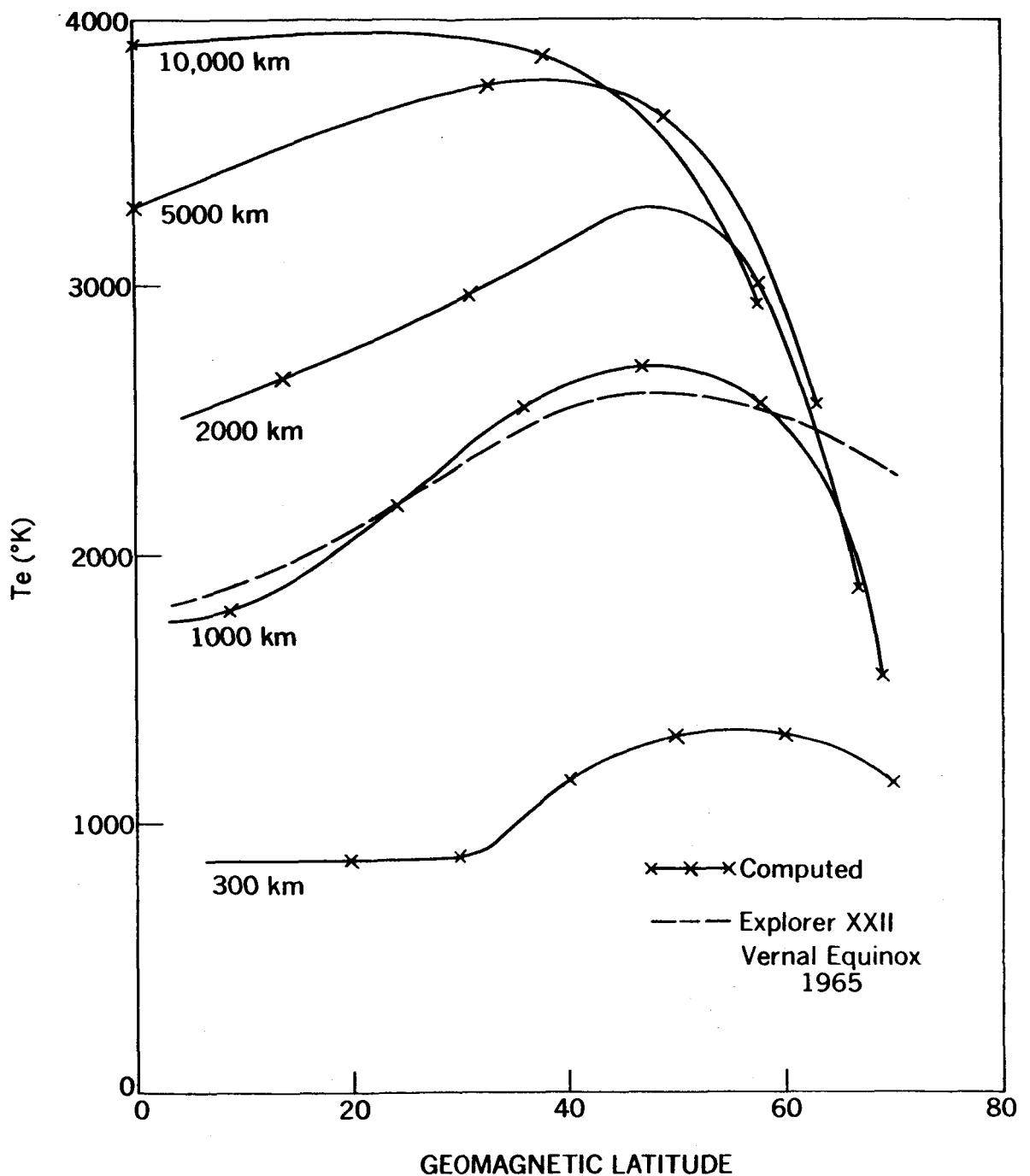


Figure 1. Computed Latitudinal Electron Temperature Distribution for Various Altitudes (Solid Lines). For Comparison the Electron Temperature at 1000 km from Explorer XXII, Vernal Equinox 1965 (Brace, Reddy, Mayr (1967)) is Shown in Dashed Line.

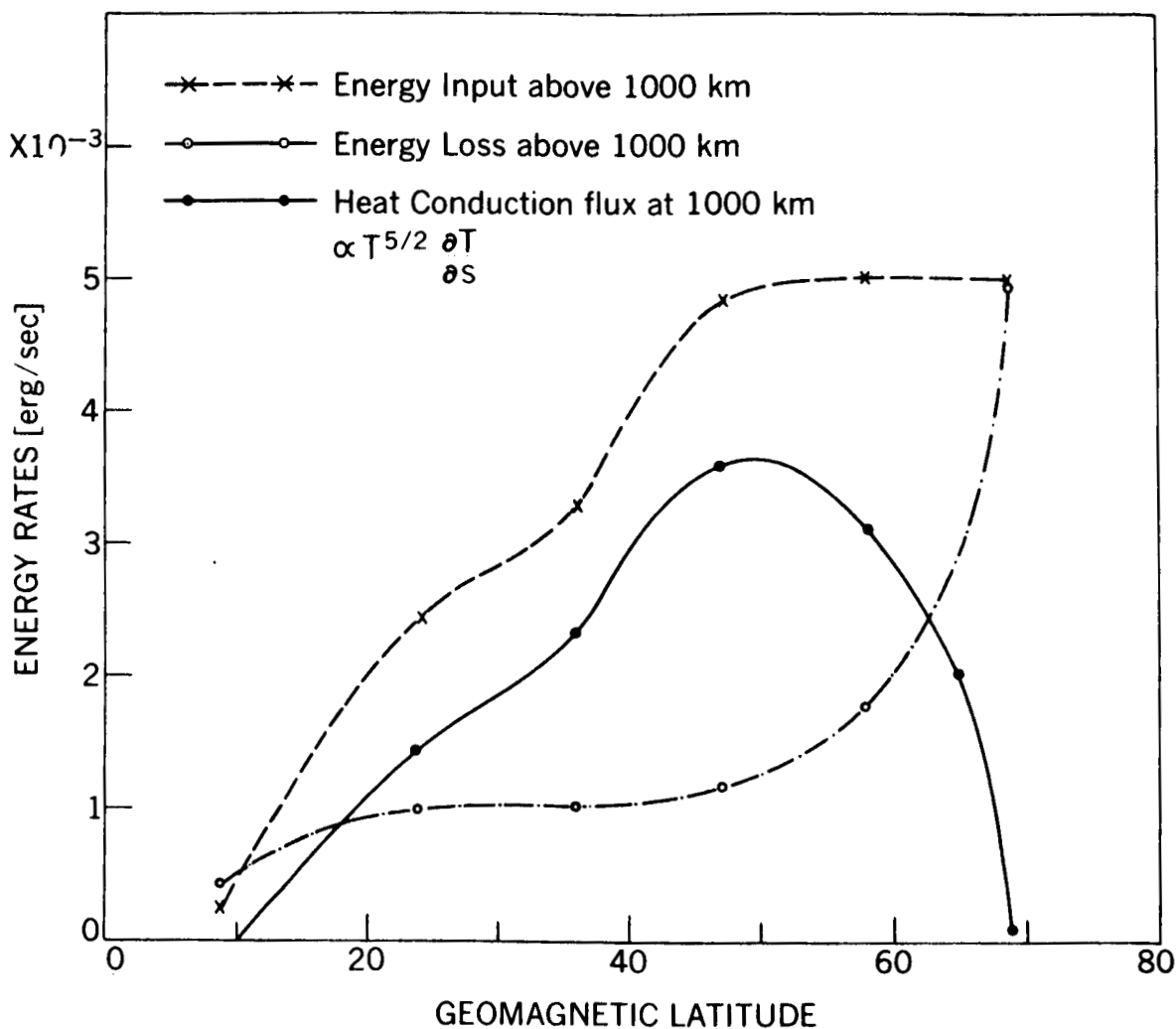


Figure 2. Energy Rates Integrated over Field Tube Volumes above 1000 km (with Basis Area of 1 cm^2): The Energy Input due to Escaping Fast Electrons (in Dashed Line), the Energy Loss Rate due to Collisions between Ions and Neutrals (in Dashed Dotted Line), and the Difference of Input Minus Loss Which is Equal to the Heat Conduction Flux at 1000 km, (Solid Line).

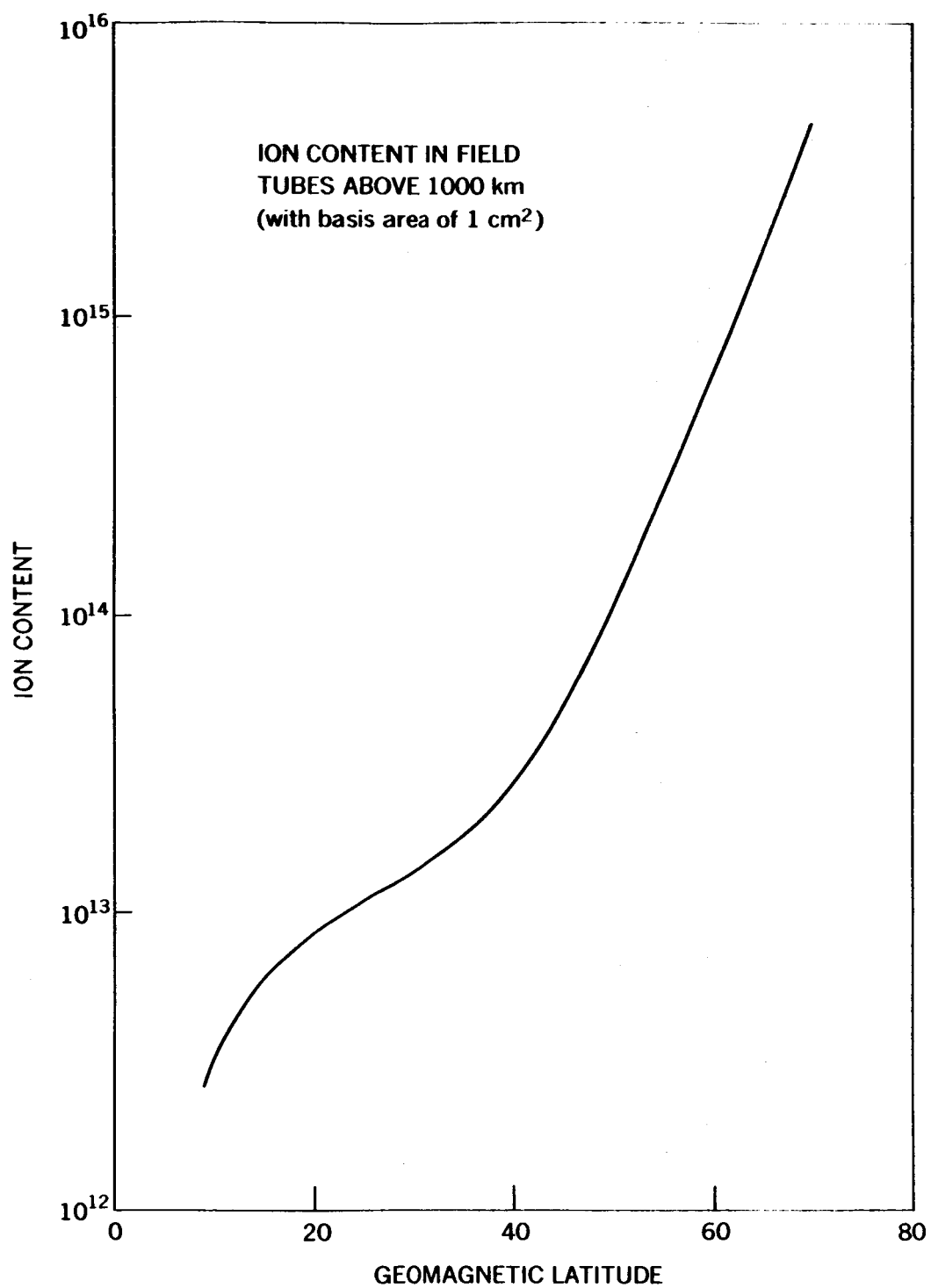


Figure 3. Ion Content in Field Tubes Above 1000 km (with Basis Area of 1 cm²) as a Function of Latitude.

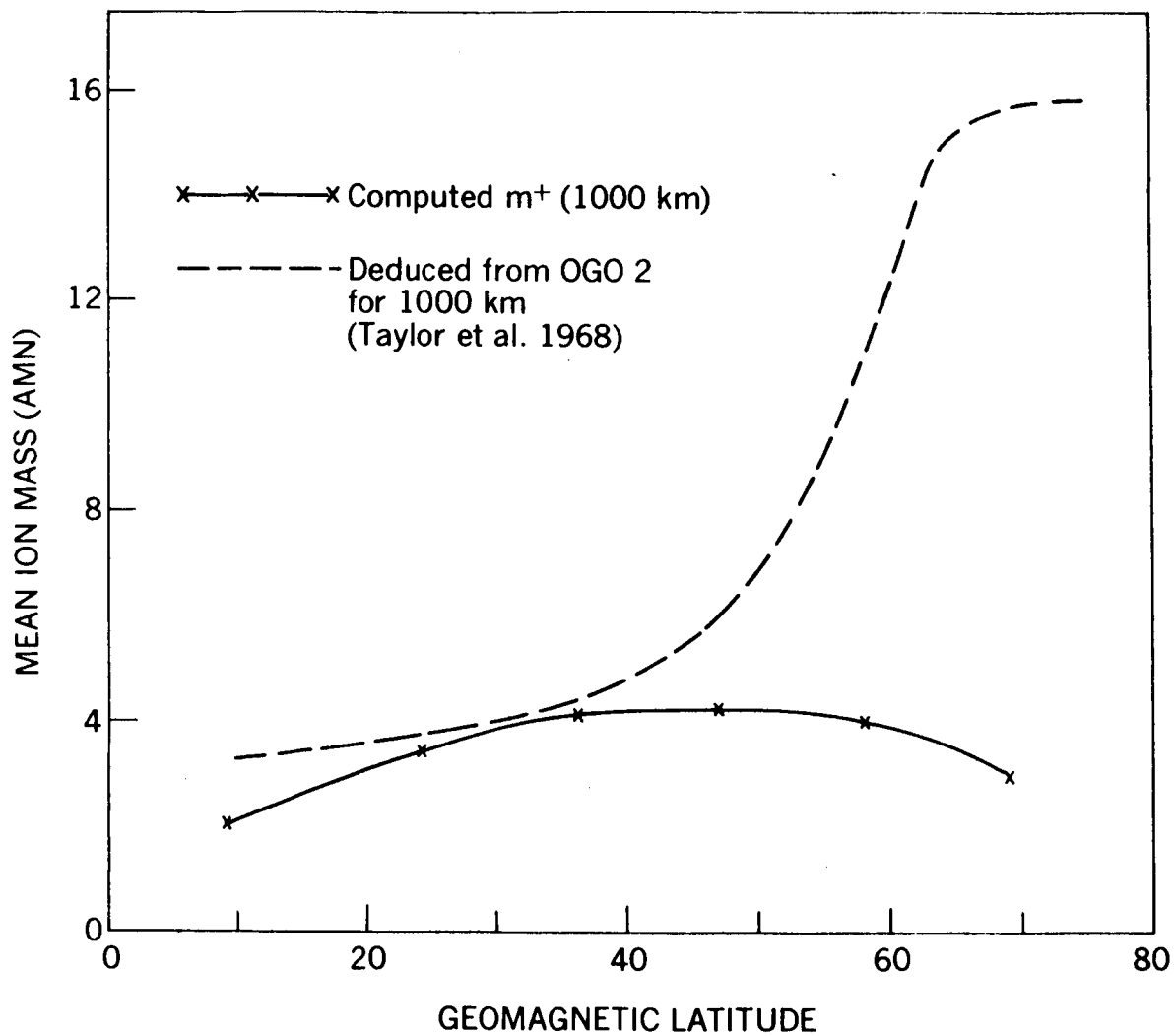


Figure 4. Computed Mean Ion Mass at 1000 km. For Comparison the Mean Ion Mass Deduced for 1000 km from OGO-2 (Taylor et al. 1968) for Dusk Period in October 1965.

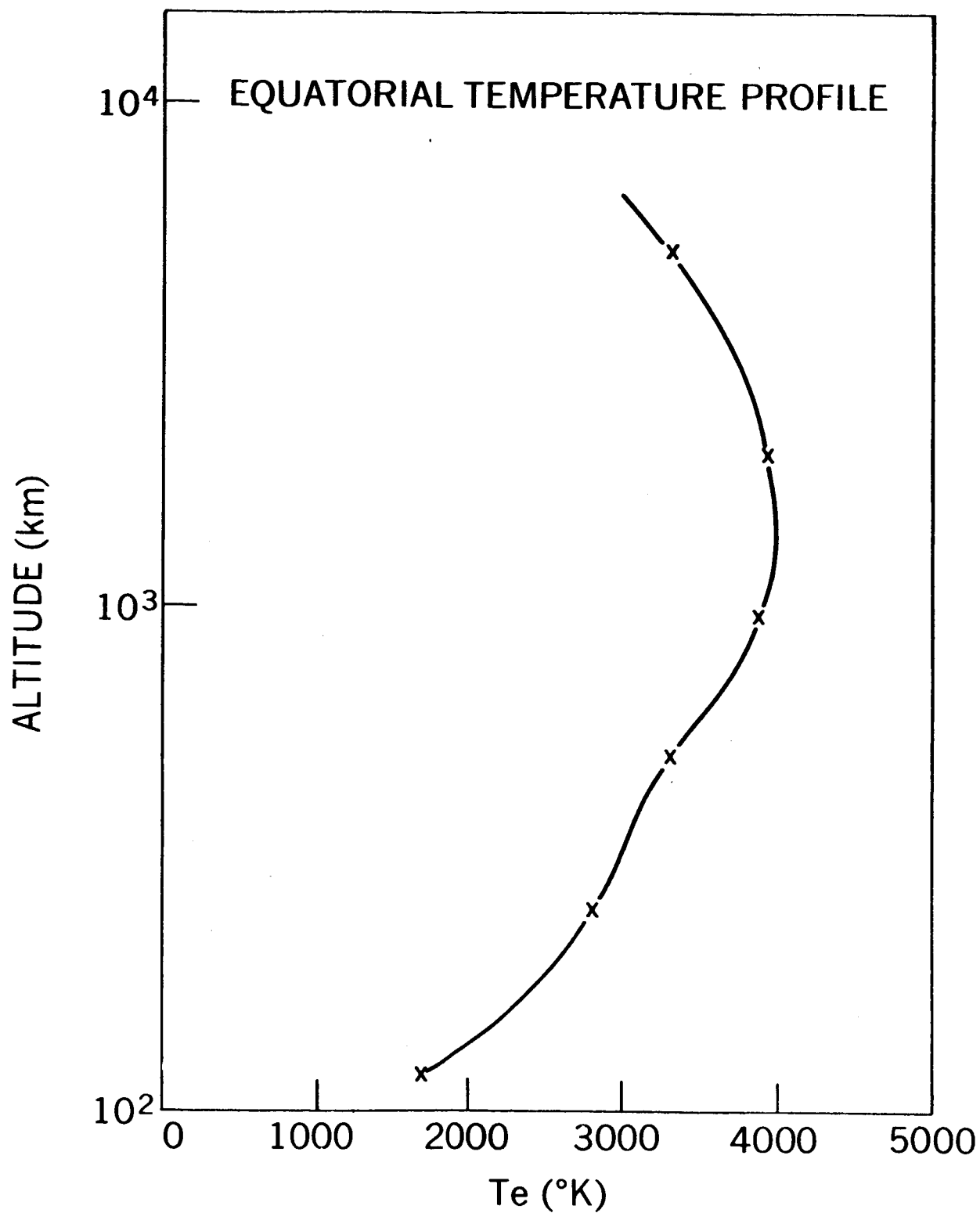


Figure 5. Computed Temperature Profile at the Equator.